RADIAL EVOLUTION OF DENSITY STRUCTURE IN THE SOLAR CORONA

Richard Woo

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Shadia Rifai Habbal

Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts

Abstract. White-light measurements by the SOHO LASCO coronagraph and HAO Mauna Loa Mk III K-coronameter are used to follow density structure in the solar corona as it evolves from 1.15 to 5.5 Ro. Global imaging confirms and strengthens earlier results from spacecraft radio ranging measurements [Woo and Habbal, 1998b], that the imprint of density structures at the Sun — as manifested in the density profile observed closest to the Sun at 1.15 Ro — is carried essentially radially into interplanetary space. The only exception is the small volume of interplanetary space occupied by the heliospheric current sheet that evolves from coronal streamers within a few solar radii of the Sun. These measurements dispel the long-held belief that the boundaries of polar coronal holes diverge significantly. They also imply that a significant fraction of field lines which extend into interplanetary space originate from the quiet Sun, and are indistinguishable in character from those emanating from polar coronal holes. These results further support the view originally proposed by Woo and Habbal [1998] that the fast solar wind originates from the quiet Sun as well as polar coronal holes.

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INTRODUCTION

Considerable growth in our observational knowledge of density structure in the corona — with significant implications for the origin and evolution of the solar wind — has taken place in recent years [Woo and Habbal, 1998a and references therein]. The boundary between the polar coronal hole and coronal streamer at the Sun was found to extend radially into interplanetary space [Woo and Habbal, 1997], instead of undergoing any significant divergence as commonly thought [Zirker, 1997; Munro and Jackson, 1977]. This unexpected result was revealed when ranging measurements of path-integrated density conducted by Ulysses in 1995 near 30 Ro were compared with corresponding white-light images by the HAO Mk III K-coronameter. Crucial to this result was the ability of the high-sensitivity Ulysses ranging measurements to probe faint and low-contrast structures far away from the large-scale closed magnetic fields comprising coronal streamers. The unprecedented sensitivity and dynamic range of the Large Angle Spectrometric Coronagraph (LASCO) on the SOHO spacecraft [Brueckner et al., 1995] made it possible to investigate and obtain additional support for the radial extension of the coronal hole boundary inside 8 Ro with white-light images [Woo et al., 1999].

In a subsequent study, the time series of path-integrated density observed by the same 1995 Ulysses ranging measurements mentioned above over a period of 20 days at 20–30 Ro was compared with that by the polarized brightness measurements of the HAO Mk III K-coronameter at 1.15 Ro. This comparison revealed that the coronal hole boundary was not an isolated feature that extended radially, but was instead an integral part of the general coronal density profile that was preserved during radial expansion [Woo and Habbal, 1998b]. In this paper, we use white-light images obtained with the HAO Mk III K-coronameter and the SOHO LASCO coronagraph to follow the evolution of density structure from 1.15 to 5.5 Ro and confirm that the imprint of the Sun, as manifested in the density profile observed closest to the Sun at 1.15 Ro, extends radially into interplanetary space.

OBSERVATIONS

We base the current study on the path-integrated density profiles of August 11, 1997 which were also used to investigate the radial extension of the coronal hole boundary [Woo et al., 1999]. The Yohkoh soft X-ray full disk image is combined with the HAO Mauna Loa Mk III K-coronameter white-light image in Figure 1a, while the Mauna Loa white-light image is in turn combined with the SOHO LASCO C2 image in Figure 1b. The SOHO LASCO C3 image is shown in Figure 1c. Since the supporting pylon of the C2 and C3 external occulters is located in the southeast quadrant of the field of view (around position angle 130°), and causes significant vignetting there, we limit this investigation to the northern hemisphere, i.e., position angles spanning ±90°.

The northern polar coronal hole, as projected on the solar disk and defined by the Kitt Peak He I 1083 nm map, is traced in yellow on the Yohkoh soft X-ray image in Figure 1a. The straight dashed yellow lines superimposed on the corona in Figures 1 a–c trace the radial extensions of the He I coronal hole boundaries in the plane of the sky, starting from the boundaries at the limb. These same boundaries have been discussed in Woo et al. [1999], and are also represented by the black vertical lines on the latitudinal profiles of the white-light intensities in Figure 2.

The profiles in Figure 2, comprising measurements sampled once per degree of latitude, are displayed on a logarithmic vertical scale in order to show more clearly relative change. The pB scans of the Mk III K-coronameter at heights of 1.15, 1.35, 1.45, and 1.55 Ro provided by J. Burkepile and H. Higgins of HAO are displayed in Figure 2a. These profiles show that density is not constant, but varies within the coronal hole. The range of variation in the pB profiles rises steeply with increasing height — from a factor of 2–3 nearest the Sun at 1.15 Ro to an order of magnitude or higher for heights greater than 1.35 Ro. In spite of the steep rise in pB levels outside the coronal hole, the shapes of the pB profiles within the coronal hole remain essentially unchanged with increasing height. However, the noisy profile at 1.55 Ro indicates that the measurements of the coronal hole are only reliable closer than this distance to the Sun. These features and the evolution of density structure with height are better illustrated in Figure 2b, where the profiles at 1.35 and 1.45 Ro have been shifted and superimposed on the 1.15 Ro profile (achieved by multiplying by factors of 9 and 25, respectively).

For measurements beyond 1.55 Ro, we use the intensity profile of C3 near the start of its field of view at 5.5 Ro where its sensitivity and dynamic range are highest [Brueckner et al., 1995]. The procedure for obtaining the C3 profile has been described in Woo et al. [1999]. We have adjusted the vertical scale of the C3 intensity so that the coronal hole profile matches that in Figure 2b, and combined the result with the profiles of Figure 2b in Figure 2c. It is clear that the evolution of streamers observed near the Sun — the narrowing of streamers accompanied by growth in streamer-relative-to-coronal hole brightness — continues at 5.5 Ro. The profiles nearest (1.15 Ro) and farthest from the Sun (5.5 Ro) are combined in Figure 2d to show the remarkable coincidence between the two over a region of large angular extent — 110° in latitude spanning position angles +60° to -50° (unshaded portion of the profiles). The coincidence between the latitudinal profiles in Figure 2d is strikingly similar to that found earlier between ranging and white-light measurements (shown in Figure 1b of Woo and Habbal [1998]), which probed a latitudinal range of 90° and found agreement over at least 60°, i.e., 120° of a hemisphere. This similarity means that the evolution of coronal streamers observed by the ranging measurements at 20–30 Ro is essentially complete by 5.5 Ro. There is also stronger evidence for radial expansion in the results of Figure 2d, because it is not necessary to use radial extrapolation of individual measurements to compare these profiles, as was done in the case in the ranging measurements.

EVOLUTION OF CORONAL HOLE

Solid radial yellow lines have been added to the images of Figure 1 to define the broad region over which the profiles in Figure 2d are preserved. At the Sun, this region encompasses as much of the quiet Sun as the polar coronal hole, with the east limb also including an active region. At 1.15 Ro, the quiet Sun dominates the profile, with its pB level showing an increase of a factor of 2–3 over that of the coronal hole and representing the ledges identified and discussed earlier [Woo et al., 1999]. At 5.5 Ro, the preserved profile is in turn dominated by the evolved coronal streamers, whose brightness is now at least an order of magnitude higher than that of the coronal hole, and which can only be detected and defined by measurements with high sensitivity and high dynamic range, as in the case of the ranging and LASCO white-light measurements. Early white-light measurements lacked these abilities, and the weaker quiet Sun signature was not observed. Consequently, polar coronal holes were thought to evolve around the edges of the bright streamers, and hence to diverge significantly [Zirker, 1977; Munro and Jackson, 1977], rather than expanding radially as is evident in Figure 2d and shown in Figure 4 of Woo et al. [1999].

The radial preservation of the profiles in Figure 2d is also remarkable because it occurs over such diverse density structures at the Sun, implying that the density fall-off with radial distance is similar for all of them. The radially preserved imprint of the quiet Sun could only have reached 5.5 Ro via solar wind flowing along approximately radial open magnetic field lines originating in the quiet Sun. While this configuration appears to contradict the long held view that open field lines are restricted to coronal holes, it is necessary to understand that coronal magnetic fields have not been measured directly, and that the traditional view is based solely on the impression of diverging polar coronal holes in white-light pictures and theoretical magnetic field modeling [Schatten et al., 1969; Pneuman and Kopp, 1971] that does not include the effect of small-scale structures. Indeed, recent high spatial resolution eclipse measurements suggest the emergence of open field lines from the quiet Sun (see Figure 5 in November and Koutchmy [1996]).

The latitudinal width of 110–120° over which density structure is preserved is similar to that over which fast solar wind was observed inside 3 Ro by SOHO UVCS measurements

[Habbal et al., 1997], as well as far from the Sun by Ulysses *in situ* plasma measurements [McComas et al., 1998]. These combined results imply that the fastest wind comes from the polar coronal holes, while the slightly slower fast wind at lower latitudes originates and flows along the open field lines from the quiet Sun, as discussed previously [Woo and Habbal, 1997, 1998b; Woo et al., 1999].

SUMMARY AND DISCUSSION

Global imaging of the solar corona by the Mauna Loa Mk III K-coronameter and LASCO coronagraph white-light measurements has been used to follow the evolution of density structure from 1.15 to 5.5 Ro. The major difference from previous white-light studies is the detection and observation of faint structure in the outer corona that had not been observed before, but detected now by the LASCO coronagraph on account of its unprecedented sensitivity and dynamic range. The white-light measurements reported here confirm and strengthen earlier results on density structure from spacecraft radio ranging measurements, including their implications for the origin and evolution of the fast solar wind, which are summarized below.

Nearest the Sun, the brightest and most dominant features of white-light images are coronal streamers, which evolve into the heliospheric current sheet within a few solar radii of the Sun. In the outer corona, the evolved narrow and bright streamer stalks [Wang et al., 1997] ironically occupy only a small volume of interplanetary space, but carry the slowest solar wind [Habbal et al., 1997]. As the streamers become narrower, more of the imprint of the Sun is revealed, eventually spanning a latitudinal range of 110-120° in a hemisphere as close as 5.5 Ro. The imprint of the Sun is carried into interplanetary space, presumably by open, approximately radial, low-density, low-contrast, small-scale magnetic field lines that pervade the corona [Woo, 1996], extending from coronal holes and threading their way through closed field regions of the quiet Sun. These small-scale structures are readily detected in radio occultation measurements, but not in white-light images. Fast wind originating from the quiet Sun as well as from coronal holes flows along these small-scale structures.

The results of this study also demonstrate how instrumental limitations (lack of sensitivity and dynamic range) of white-light measurements before LASCO prevented them from defining faint structure in polar regions of the upper corona (e.g., beyond 1.5 Ro in the case of the Mk III measurements). Without this crucial information, the boundaries of the bright streamers in white-light pictures that appeared to follow the large-scale dipolar field were mistaken for coronal hole boundaries, and polar coronal holes were erroneously concluded to diverge significantly with radial expansion. Along with magnetic field modeling, this result led to the idea that open field lines existed solely in coronal holes, and the natural conclusion that the high latitude fast wind observed by Ulysses *in situ* plasma measurements all came from polar coronal holes [Gosling et al., 1995; Geiss et al., 1995; McComas et al., 1998].

It is interesting to realize how path-integrated measurements impaired as well as aided in the search for the elusive connection between Sun and interplanetary space. In the inner corona, white-light images showed a wealth of coronal structures. The low density structures associated with open field lines and overlying the quiet Sun were masked by the brighter structures associated with closed field lines, giving the false impression that the solar magnetic field was essentially only that of a dipole. However, once the measurements took place higher in the corona and beyond the closed field lines, the structure associated with the faint open magnetic field lines that had thread its way through the closed field regions was revealed. In the outer corona the global aspect of path-integration measurements became an advantage, because it led to the unambiguous conclusion that the imprint of the Sun was observed there. Reaching such a conclusion strictly on the basis of *in situ* point measurements made directly by a spacecraft would have been difficult. For this reason, the importance of complementing *in situ* point measurements on a mission like Solar Probe with imaging and radio propagation measurements that detect faint, low-contrast, small-scale structures is clear.

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REFERENCES

Brueckner, G.E., et al., The large angle spectroscopic coronagraph (LASCO), *Solar Phys.*, *162*, 357–402, 1995.

Geiss, J., et al., The southern high-speed stream: Results from the SWICS instrument on Ulysses, *Science*, *268*, 1033–1036, 1995.

Gosling, J.T., et al., The band of solar wind variability at low heliographic latitudes near solar activity minimum: Plasma results from the Ulysses rapid latitude scan, *Geophys. Res. Lett.*, *22*, 3329–3332, 1995.

Habbal, S.R., Woo, R., Fineschi, S., O'Neal, R., Kohl, J., Noci, G., and Korendyke, C., Origins of the slow and the ubiquitous fast solar wind, *Astrophys. J.*, *489*, L103–106, 1997.

McComas, D.J., et al., Ulysses' return to the slow solar wind, *Geophys. Res. Letts.*, *25*, 1–4, 1998.

Munro, R.H., and Jackson, B.V., Physical properties of a polar coronal hole from 2 to 5 R_O, *Astrophys. J.*, *213*, 874–886, 1977.

November, L.J., and Koutchmy, S., White-light coronal dark threads and density fine structure, *Astrophys. J.*, *466*, 512, 1996.

Pneuman, G.W., and Kopp, R.A., Gas-magnetic field interactions in the solar corona, *Solar Phys.*, *18*, 258, 1971.

Schatten, K.H., Wilcox, J.M., and Ness, N.F., A model of interplanetary and coronal magnetic fields, *Solar Phys.*, *6*, 442, 1969.

Wang, Y.-M., et al., Origin and evolution of coronal streamer structure during the 1996 minimum activity phase, *Astrophys. J.*, *485*, 875–889, 1997.

Woo, R., Kilometre-scale structures in the Sun's corona, *Nature*, *379*, 321–322, 1996.

Woo, R., and Habbal, S.R., Extension of coronal structure into interplanetary space, *Geophys. Res. Lett.*, *24*, 1159–1162, 1997.

Woo, R., and Habbal, S.R., Multiscale filamentary structures in the solar corona and their implications for the origin and evolution of the solar wind, in *Physics of Space Plasmas (1998). Number 15*, eds. T. Chang and J.R. Jasperse, MIT Center for Theoretical Geo/Cosmo Plasma Physics, Cambridge, MA, 1998a.

Woo, R., and Habbal, S.R., Imprint of the sun on the solar wind, *Astrophys. J.*, 1998b, in press.

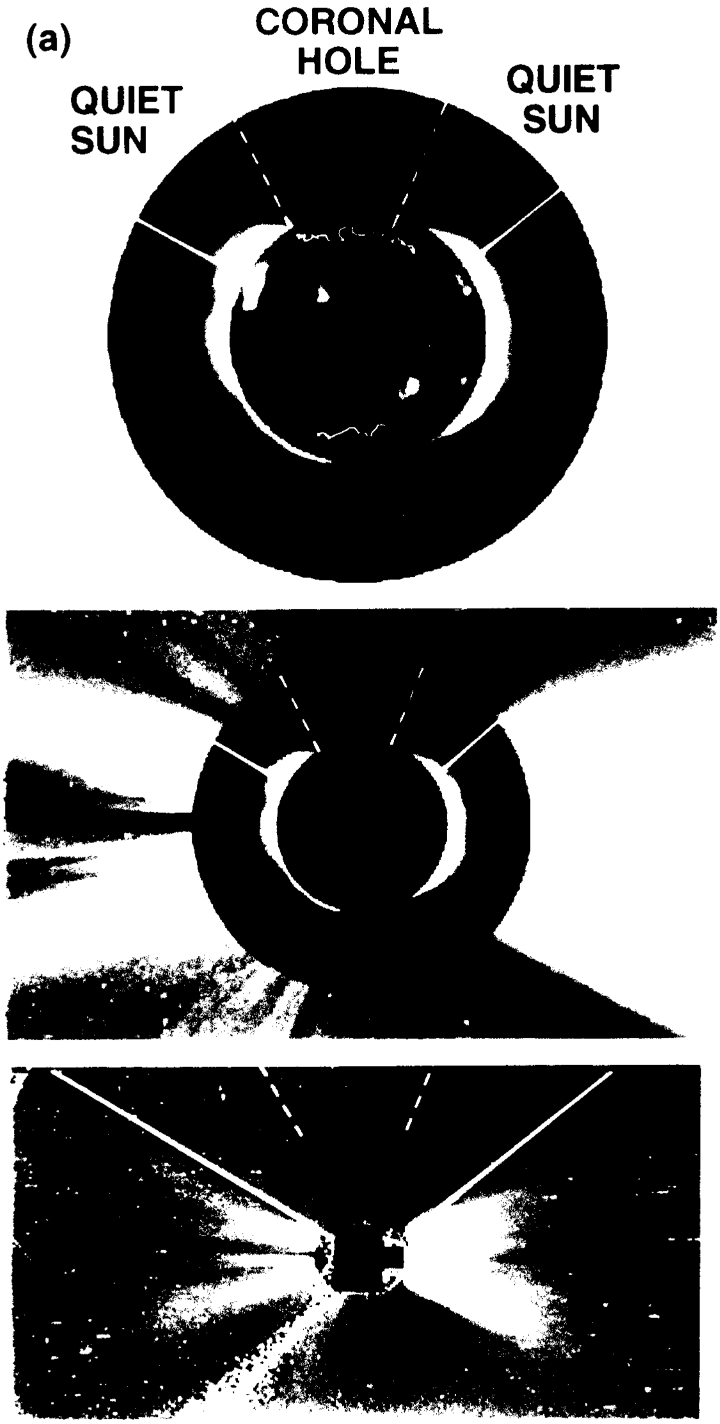
Woo, R., Habbal, S.R., Howard, R.A., and Korendyke, C.M., Extension of the polar coronal hole boundary into interplanetary space, *Astrophys. J.*, 1999, in press.

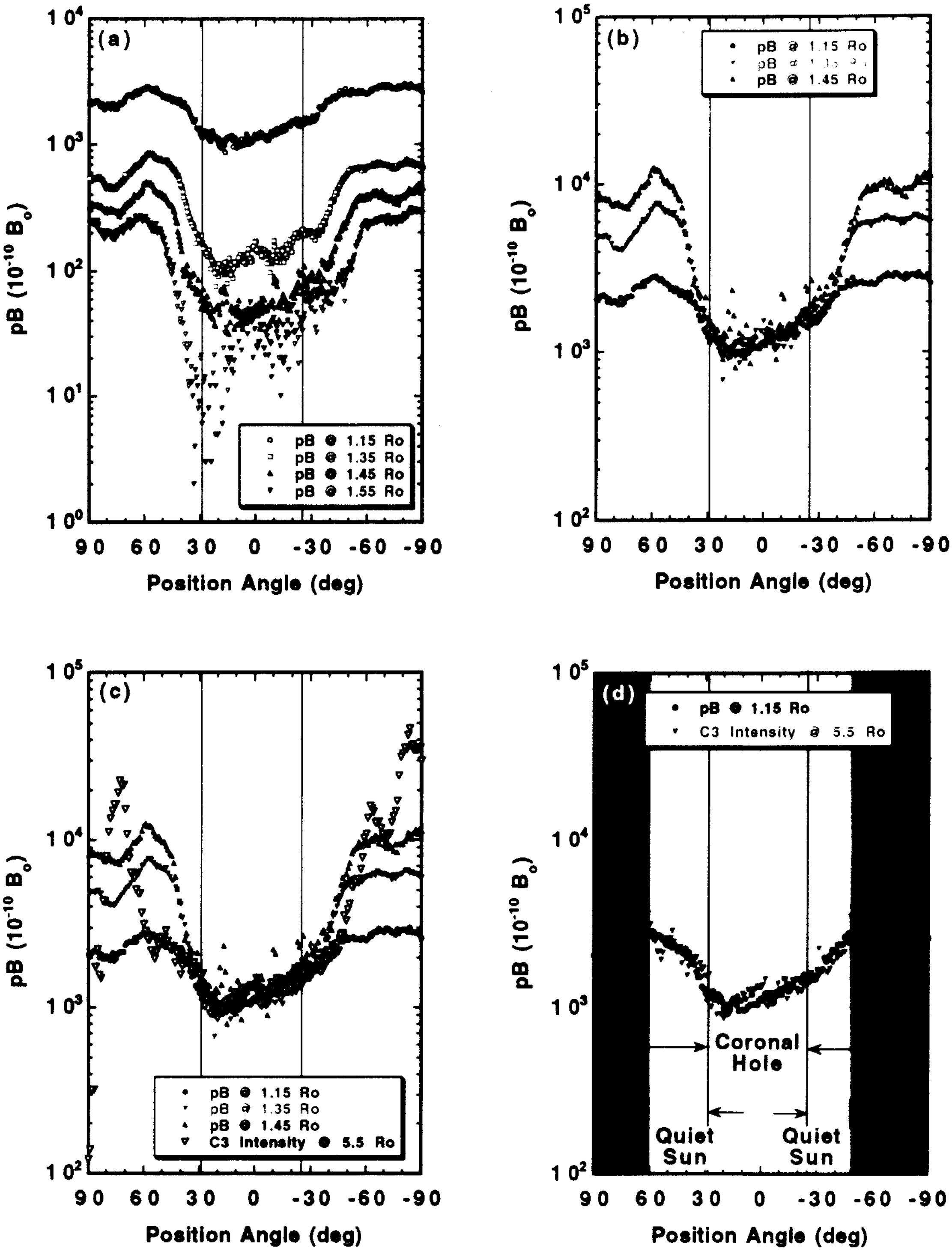
Zirker, J.B., ed., *Coronal Holes and High Speed Wind Streams*, Colorado Associated University Press, Boulder, 1977.

Figure Captions

Figure 1. White-light observations of August 11, 1997. (a) Combined images of Yohkoh soft X-ray and Mk III Mauna Loa K-coronameter pB. The yellow line on the disk traces the coronal hole boundary as defined by the He I 1083 nm maps of the National Solar Observatory. (b) Combined images of SOHO LASCO C2 intensity and Mauna Loa pB. (c) Image of LASCO C3 intensity. The dashed yellow lines superimposed on the corona (and corresponding to the black vertical lines in Figure 2) indicate the radial extension of the polar coronal hole boundaries as defined by the He I 1083 nm maps; the solid yellow lines indicate the region over which there is coincidence between the density profiles at 1.15 and 5.5 Ro, as defined by the unshaded portions of the profiles in Figure 2d.

Figure 2. Latitudinal profiles of path-integrated density. The black vertical lines correpond to the coronal hole boundaries defined by the dashed yellow lines in Figure 1. (a) pB observed by Mk III Mauna Loa K-coronameter at altitudes of 1.15, 1.35, 1.45, and 1.55 Ro. (b) Superimposed Mk III pB profiles at 1.15, 1.35, 1.45 Ro. (c) SOHO C3 intensity profile at 5.5 Ro superimposed on profiles of (b). (d) SOHO C3 intensity profile at 5.5 Ro superimposed on Mk III pB profile at 1.15 Ro. The unshaded portions of the profiles are where there is coincidence between the two.


(a)
CORONAL
HOLE
QUIET
SUN
QUIET
SUN


(a)
pB @ 1.15 Ro
pB @ 1.35 Ro
pB @ 1.45 Ro
pB @ 1.55 Ro
pB (10^{-10} B_o)
Position Angle (deg)
(b)
pB @ 1.15 Ro
pB @ 1.45 Ro
pB (10^{-10} B_o)
Position Angle (deg)
(c)
pB @ 1.15 Ro
pB @ 1.35 Ro
pB @ 1.45 Ro
C3 Intensity @ 5.5 Ro
pB (10^{-10} B_o)
Position Angle (deg)
(d)
pB @ 1.15 Ro
C3 Intensity @ 5.5 Ro
Coronal Hole
Quiet Sun
Quiet Sun
pB (10^{-10} B_o)
Position Angle (deg)